

The X-ray properties of young radio-loud AGN

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ABSTRACT

We present *XMM-Newton* observations of a complete sample of five archetypal young radio-loud AGN, also known as Compact Symmetric Objects (CSO) or Gigahertz Peaked Spectrum (GPS) sources. They are among the brightest and best studied GPS/CSO sources in the sky, with radio powers in the range $L_{5\text{GHz}} = 10^{43-44} \text{ erg s}^{-1}$ and with four sources having measured kinematic ages of 570 to 3000 years. All five sources are detected, and have 2–10 keV luminosities ranging from 0.5 to $4.8 \times 10^{44} \text{ erg s}^{-1}$. A detailed analysis was performed, comparing the X-ray luminosities and N_{H} absorption column densities of the GPS/CSO galaxies with their optical and radio properties, and with those of the general population of radio galaxies. We find that,

- 1) GPS/CSO galaxies show a wide range in absorption column densities with a distribution not different from that of the general population of radio galaxies. We therefore find no evidence that GPS/CSO galaxies could reside in a significantly more dense circumnuclear environment such that they could be “frustrated” radio sources – hampered in their development.
- 2) The ratio of radio to X-ray luminosity is significantly higher for GPS/CSO sources than for classical radio sources. This is consistent with an evolution scenario in which young, compact radio sources are more efficient radio emitters than large extended objects, at a constant accretion power.
- 3) Taking the X-ray luminosity of radio sources as a measure of their ionisation power, we find that GPS/CSO sources are significantly underluminous in their $[\text{OIII}]_{5007\text{\AA}}$ line luminosity, including a weak trend with age. This is consistent with the fact that the Strömgren sphere should still be expanding in these young objects. If true, this would mean that here we are witnessing the birth of the narrow line region of radio-loud AGN.

Key words: galaxies: active – X-ray: galaxies

1 INTRODUCTION

Ever since their discovery, it has been speculated that those compact radio sources that show convex-shaped radio spectra at cm wavelengths, may be young objects (Shklovsky 1965; Blake 1970). As a class, they were named Gigahertz Peaked Spectrum (GPS) sources after their characteristic radio spectrum (see O’Dea 1998, for a review), most likely caused by synchrotron self absorption (Fanti et al. 1990; Snellen et al. 2000, e.g.). High resolution Very Long Baseline Interferometry (VLBI) observations have shown that these sources are typically up to a few hundred parsec in size, often exhibiting jet and/or lobe structures on two opposite sides from their central core – the reason why they are also called Compact Symmetric Objects (CSO; eg. Wilkinson et al. 1994). The most compelling evidence that GPS/CSO are indeed

young radio sources comes from VLBI monitoring observations, showing that the bright archetypal objects in this class have hot-spot propagation velocities of $\sim 0.1\text{--}0.2c$ (Owsianik & Conway 1998; Owsianik et al. 1998; Tschager et al. 2000), indicating kinematic ages of $\sim 10^3$ years. This is in contrast to speculations that GPS/CSO galaxies are small due to confinement by a particularly dense and clumpy interstellar medium (ISM) that impedes the outward propagation of the jets (van Breugel et al. 1984; O’Dea et al. 1991).

Note that a large fraction of GPS sources, in particular those showing a convex radio spectrum peaking at higher frequencies than a few GHz, turn out to be identified with high redshift quasars ($z \sim 2\text{--}3$). Their connection with the population of GPS/CSO galaxies at lower redshift is not clear, and they may well be a completely separate class of object which just also happen to exhibit a convex shaped spectrum (Snellen et al. 1999). By no means it has been es-

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Table 1. The sample of GPS/CSO radio sources with $|b| > 20^\circ$ from the Pearson & Readhead (1988) catalogue. Indicated are, (column 1) the coordinates, (column 2) redshift, z , (column 3) radio flux density at 5 GHz, $S_{5\text{GHz}}$ (erg s $^{-1}$), (column 4) radio luminosity at 5 GHz, $L_{5\text{GHz}}$ (erg s $^{-1}$), (column 5) the 5007 Å [O III] emission line luminosity, $L_{[\text{OIII}]}$ (erg s $^{-1}$) from Lawrence et al. (1996), and (column 6) the kinematic age of the radio hot spots (Polatidis & Conway 2003, except for B1358+624)

| Source | Position (J2000) | z | $S_{5\text{GHz}}^a$ Jy | $\log L_{5\text{GHz}}$ | $\log L_{[\text{OIII}]}$ | Kinematic Age yr |
|-----------|--|-------|---------------------------|------------------------|--------------------------|--------------------------|
| B0108+388 | 01 ^h 11 ^m 37.3 ^s +39°06′28″ | 0.668 | 1.6 | 44.0 | 40.8 | 570 ± 50 |
| B0710+439 | 07 ^h 13 ^m 38.1 ^s +43°49′17″ | 0.518 | 1.6 | 43.7 | 42.4 | 930 ± 100 |
| B1031+567 | 10 ^h 35 ^m 07.0 ^s +56°28′47″ | 0.45 | 1.3 | 43.4 | 41.6 | 1800 ± 600 |
| B1358+624 | 14 ^h 00 ^m 28.6 ^s +62°10′39″ | 0.431 | 1.8 | 43.5 | 41.8 | 2400 ± 1000 ^b |
| B2352+495 | 23 ^h 55 ^m 09.4 ^s +49°50′08″ | 0.238 | 1.5 | 43.0 | 41.3 | 3000 ± 750 |

^a Obtained from the NASA/IPAC Extragalactic Database (NED)

^b The kinematic age of B1358+624 has not been directly measured, but is based on its size and the average size-age relation of GPS/CSO sources in Polatidis & Conway (2003).

established that the GPS quasars may also represent a young stage of radio source evolution.

Here we present *XMM-Newton* X-ray observations of a small but complete sample of all five GPS sources from the Pearson & Readhead (1988) sample with Galactic latitude $|b| > 20^\circ$ (Table 1). These are among the brightest GPS/CSO galaxies in the sky. All these sources appear to be young radio loud AGN with four out of five sources having measured kinematic ages of their hot spots, indicating ages of up to ~ 3000 yr. No kinematic age measurement for B1358+624 exists, but based on its size and the age-size measurements of GPS/CSO sources (Polatidis & Conway 2003) we estimate its age to be 2400 yr. Although the sample is limited in size, it allows us to study the correlations between their X-ray, optical and radio properties, and to assess how they compare to those of mature radio galaxies. One expects that the X-ray luminosity is largely a manifestation of the instantaneous accretion power of the central black hole, whereas the radio luminosity is expected to evolve substantially over the life time of the source (Readhead et al. 1996; Snellen et al. 2000, e.g.). Moreover, X-ray absorption measurements are an excellent means to probe the circum nuclear density of the GPS galaxies.

Several papers on X-ray observations of GPS sources have appeared in the literature, but one should be cautious to interpret these results in terms of X-ray properties of young radio-loud AGN. A first success was obtained by (O’Dea et al. 2000) with ASCA. Although they did not detect B2352+495, they obtained a firm detection of GPS galaxy B1345+125 (PKS1345+125). Furthermore, Guainazzi et al. (2004) detected B1404+288 (Mkn 668).¹ Both are low redshift GPS galaxies exhibiting strong optical line emission and are powerful infrared emitters, and may be not representative to the class of young radio-loud AGN (yet no reliable ages have been measured for these sources). The combined X-ray and radio observations of the GPS quasar B0738+313 presented by Siemiginowska et al. (2003) show that, with its prominent kpc-scale X-ray/radio jet, it is certainly not a young radio-loud AGN.

In order to easily compare our results for GPS/CSO galaxies with the X-ray properties of a large sample of AGN by Sambruna et al. (1999) we adapt here a cosmology with $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

¹ Prior to the submission of this publication we learned that Guainazzi et al. have detected a number of other GPS/CSO galaxies in X-rays, which do not overlap with our sample (Guainazzi et al. 2005)

Table 2. Log of the *XMM-Newton* observations. The MOS exposure time and event rates refer to the average value for MOS1 and MOS2.

| Source | Observation ID | Start Date d/m/y | Exposures (MOS/PN) ks | Event rates (MOS/PN) ct s $^{-1}$ |
|-----------|----------------|---------------------|-----------------------------|---|
| B0108+388 | 0202520101 | 09/01/2004 | 16.4/12.0 | 1.6/13.6 |
| B0710+439 | 0202520201 | 22/01/2004 | 14.2/11.2 | 3.2/26.6 |
| B1031+567 | 0202520301 | 21/10/2004 | 22.2/12.8 | 34.4/93.0 |
| B1358+624 | 0202520401 | 14/04/2004 | 12.4/12.0 | 23.2/120.6 |
| B2352+495 | 0202520501 | 25/12/2004 | 15.8/12.8 | 3.7/28.5 |

NOTE – The event rates refer to the total detector count rates, not the source count rates.

2 OBSERVATIONS, SPECTRAL ANALYSIS AND RESULTS

XMM-Newton (Jansen et al. 2001) observed the five GPS/CSO sources as part of its guest observation program from January to December 2004 (Table 2). All observations were made with the “Thin1” optical blocking filter. For the data reduction we used the standard *XMM-Newton* software package SAS v6.0.0. Unfortunately several observations were plagued by a high particle background (see Table 2). In the case of B0108+388, B0710+439, B2325+495 we removed time intervals with a high background count rate, using cut off rates of 15.5 ct s $^{-1}$ and 2.5 ct s $^{-1}$ for resp. PN and MOS. For B1031+567 and B1358+624 the high background persisted throughout the observation, and we simply used all available data. The observation B2325+495 had an intermediate background activity, so we selected time intervals with $< 40 \text{ ct s}^{-1}$ and $< 5 \text{ ct s}^{-1}$ for PN and MOS. For spectral extraction we used circular extraction regions with radii of 15″ for B1031+567 and B1358+624, and 25″ for the other three sources. Background spectra were obtained from rectangular regions near the source position, but excluding regions around 35″ of the source. We extracted spectra for the two MOS CCD cameras (Turner et al. 2001), and the PN camera (Strüder et al. 2001). For each source we combined the spectra of MOS1 and MOS2, into one spectrum, which we analysed using averaged instrumental response matrices. The potential systematic error introduced is small compared to the statistical errors, given the fact that the MOS1 and MOS2 are virtually identical instruments with similar instrumental response functions.

All the five sources of the sample are detected. For the spec-

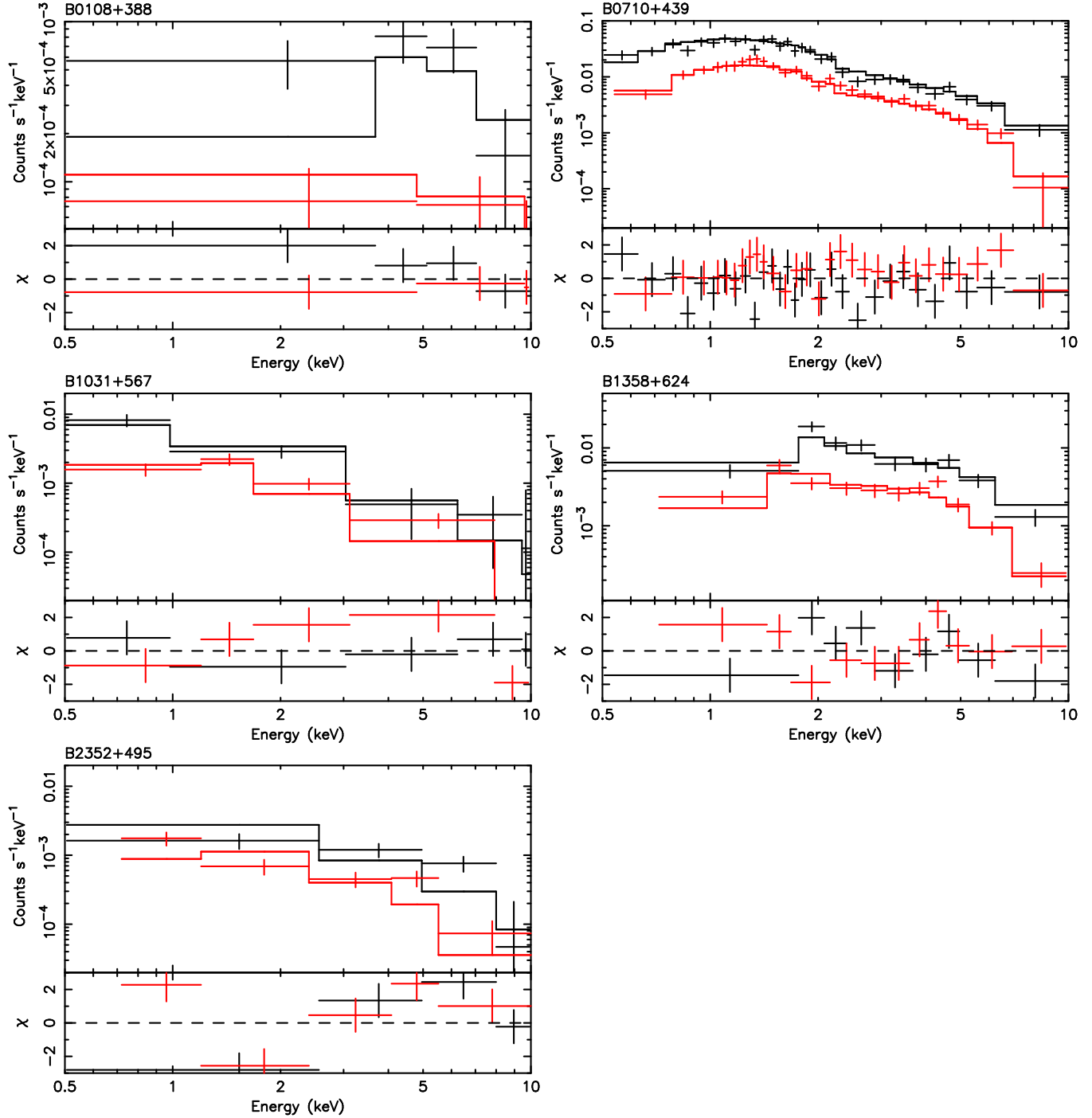


Figure 1. Observed *XMM-Newton* count rate spectra. The MOS spectra are shown in red and the PN spectra in black.

tral analysis we employed a simple model consisting of a power law continuum and two absorption components: One represents the Galactic absorption, with an absorption column, N_{H} , fixed to the Galactic value of Dickey & Lockman (1990)². The other absorption component corresponds to the absorption column intrinsic to the host galaxy. The redshift of this component was fixed to that of the galaxy, but the absorption column density was a free param-

eter. The spectral analysis was done with the spectral fitting program *xspec* (Arnaud 1996), using the absorption models of Wilms et al. (2000) (called *tbabs* and *ztbabs* in *xspec*).

The slope of the power law continuum was a free parameter for the high signal to noise spectra of B0710+439 and B1358+624, but fixed to 1.75 for the other three sources whose spectra are statistically more limited. The best fit parameters, together with the inferred intrinsic X-ray luminosities between 2-10 keV are listed in Table 3. The spectra and best fit models are shown in Fig. 1.

² We extracted the absorption columns from the online “ N_{H} -tool”, <http://heasarc.gsfc.nasa.gov/Tools>

Table 3. Observational properties and parameters obtained by modeling the observed X-ray spectra in the range 0.5-10 keV.

| | B0108+388 | B0710+439 | B1031+567 | B1358+624 | B2352+495 |
|--|-----------------|-----------------|-----------------|-----------------|-----------------|
| PN 0.5-10 keV source count rate (10^{-3} cts s^{-1}) | 4.7 ± 0.9 | 89.5 ± 3.0 | 12.6 ± 2.0 | 44.3 ± 2.7 | 8.6 ± 1.2 |
| MOS1+2 0.5-10 keV source count rate (10^{-3} cts s^{-1}) | 0.71 ± 0.25 | 33.0 ± 1.1 | 4.3 ± 0.5 | 15.8 ± 0.9 | 3.4 ± 0.4 |
| Galactic N_H (10^{20} cm^{-2}) | 5.80 | 8.11 | 0.56 | 1.96 | 12.4 |
| Normalization ^a ($10^{-5} \text{ ph s}^{-1} \text{ keV}^{-1} \text{ cm}^{-2}$ @ 1 keV) | 3.3 ± 1.1^b | 8.1 ± 0.6 | 1.2 ± 0.2 | 6.1 ± 1.6 | 1.1 ± 0.2 |
| Power law slope ^c (Γ) | (1.75) | 1.59 ± 0.06 | (1.75) | 1.24 ± 0.17 | (1.75) |
| Intrinsic N_H (10^{22} cm^{-2}) | 57 ± 20^d | 0.44 ± 0.08 | 0.50 ± 0.18 | 3.0 ± 0.7 | 0.66 ± 0.27 |
| Flux (2-10 keV) ^e ($10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$) | 0.50 | 4.0 | 0.51 | 4.8 | 0.41 |
| Luminosity (2-10 keV) ^f ($10^{44} \text{ erg s}^{-1}$) | 1.18 | 2.16 | 0.22 | 1.67 | 0.046 |
| C-statistic/bins | 137.5/99 | 497.4/401 | 104.2/97 | 122.9/99 | 126.3/99 |

^a Statistical errors correspond to $\Delta C = 1$ (68% confidence limits).

^b The 3σ lower limit is $1.1 \times 10^{-5} \text{ ph s}^{-1} \text{ keV}^{-1} \text{ cm}^{-2}$. The source is detected at the 7σ level.

^c Brackets indicate that the power law slope was fixed to this value.

^d The 3σ lower limit is $1.8 \times 10^{23} \text{ cm}^{-2}$.

^e Including absorption.

^f Calculated for rest frame energies, ignoring absorption.

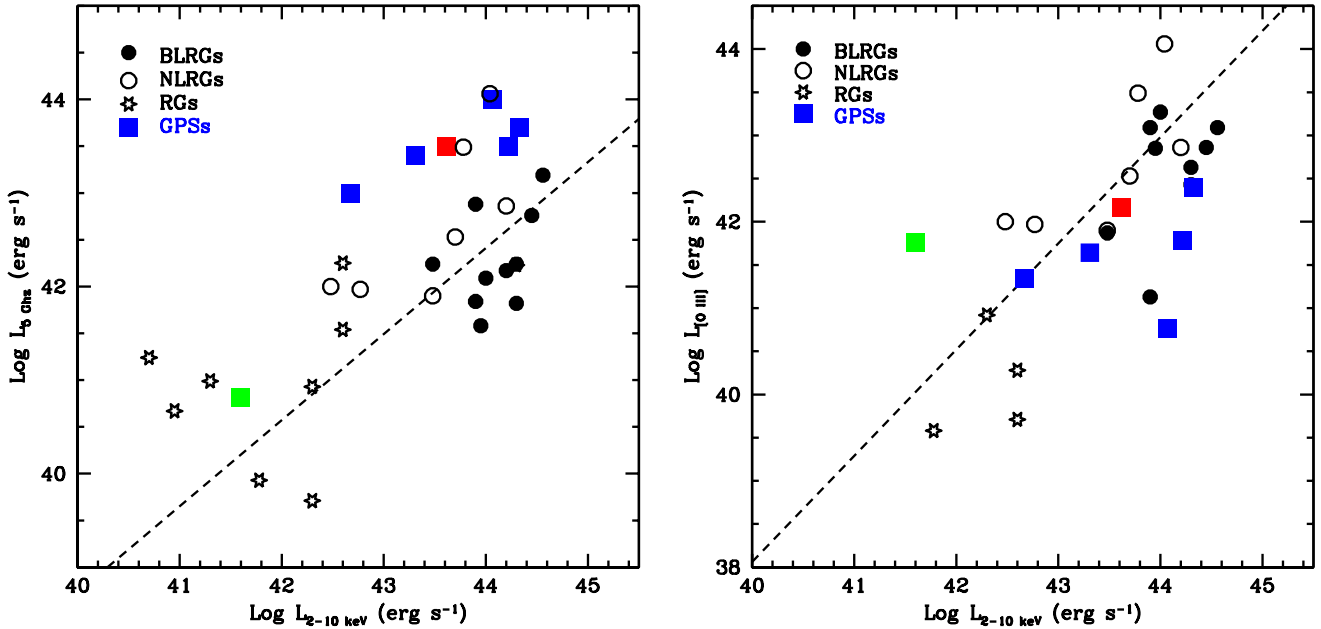


Figure 2. Left: Correlation between X-ray luminosity and radio luminosity of GPS/CSO sources (filled squares), compared to the radio-loud sample of active galactic nuclei by Sambruna et al. (1999). Right: Idem, for the [O III] line emission. In both figures the dotted lines are the average correlations for the radio loud sample obtained by Sambruna et al. (1999). The galaxies from the current sample are shown in blue, whereas Mkn 668 and PKS1345+125 are shown in green and red, respectively. .

3 INTERPRETATION

As we are interested in whether GPS/CSO galaxies are different from other radio-loud AGN we compare their X-ray properties to those of the sample of radio-loud AGN whose X-ray properties were determined by Sambruna et al. (1999) from ASCA observations. We use all the sources of their broad line radio galaxies (BLRG), narrow line radio galaxies (NLRG) and radio galaxies (RG) subsamples. Since Sambruna et al. (1999) do not quote upper

limits for the non-detected intrinsic X-ray absorption components, we estimate upper limits proportional to the observed flux taking into account the errors on the detected intrinsic absorption components.

In Fig. 2 we have set out the radio and [O III] luminosities of the galaxies in our sample to their X-ray luminosities, and we compare them to the Sambruna et al. (1999) sample. In Fig. 3 we show the intrinsic absorption column density distribution.

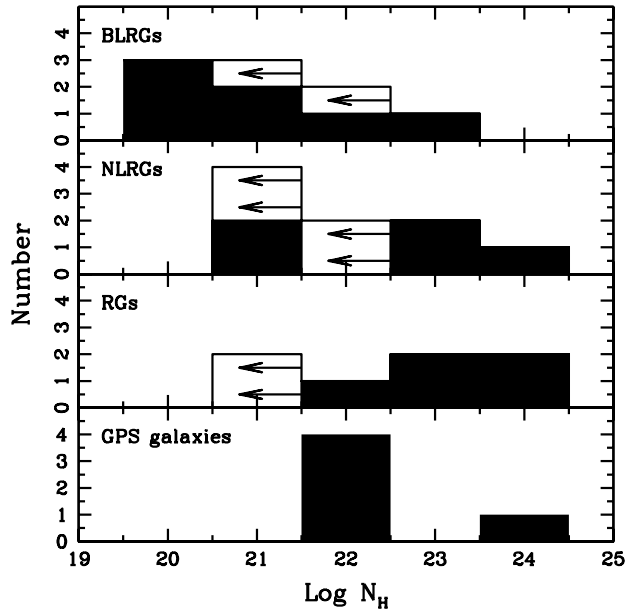


Figure 3. The distribution of the intrinsic X-ray column densities for various radio loud AGN. The lower panel are the results of the present study, the other panels have been taken from Sambruna et al. (1999). Upper limits are indicated by arrows.

Table 4. A comparison of the X-ray derived absorption column N_H and radio absorption column measurements N_{HI} (Pihlström et al. 2003).

| | $\log N_H$ | $\log N_{HI}$ |
|-----------|------------|---------------|
| B0108+388 | 23.8 | 21.9 |
| B1031+567 | 21.7 | < 20.1 |
| B1358+624 | 22.5 | 20.3 |
| B2352+495 | 21.8 | 20.5 |

These figures reveal three important properties of our sample of GPS/CSO galaxies: 1) for their X-ray emission GPS/CSO galaxies are relatively radio-loud; 2) their [O III] emission is relatively low; 3) the column density distribution is similar to those of radio-loud AGN classified by Sambruna et al. (1999) as narrow line radio galaxies (NLRGs) and radio galaxies (RGs), but the absorption is on average higher than those of broad line radio galaxies.

As we discuss below these three properties support the hypothesis that GPS/CSO galaxies are indeed young radio-galaxies. Note that there are strong indications that GPS radio galaxies have relatively low [O III] luminosities with respect to their radio luminosities as compared to compact steep spectrum (CSS) sources (O’Dea 1998). This is probably the same trend between radio, [O III], and X-ray luminosity that we report here, but without the X-ray luminosity as intermediary quantity. As noted in the introduction, the X-ray luminosity is the quantity that is probably the best indicator for the intrinsic power of the AGN.

3.1 The absorbing column density

An alternative explanation for the small extent of the radio jets in GPS/CSO galaxies that is still often considered in the literature (O’Dea 1998) is that the radio jets are quenched by a high density in the vicinity of the nucleus, in other words they are “frustrated radio

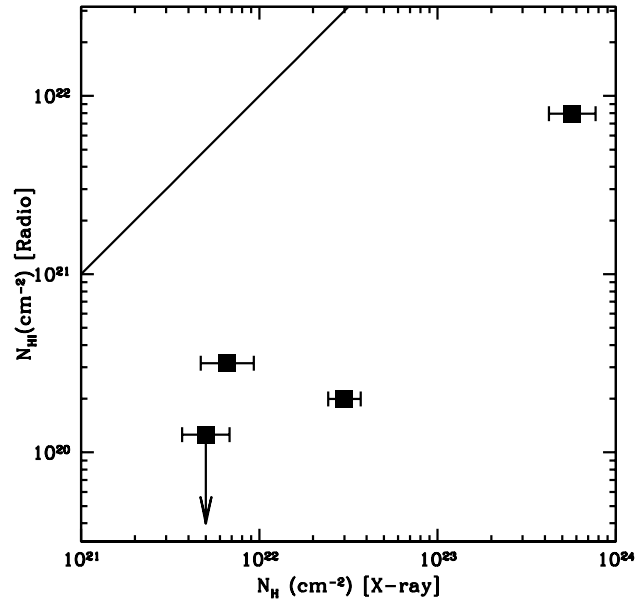


Figure 4. The neutral hydrogen absorption column density, N_{HI} , toward the radio source (Pihlström et al. 2003) versus the intrinsic X-ray absorption column density, N_H , for the four sources for which N_{HI} is measured. The solid line indicates $N_{H/X-ray} = N_{HI}$, the arrow indicates an upper limit.

sources”. It is clear from Table 3 and Fig. 3 that this is unlikely to be the case, as the intrinsic X-ray absorption is similar to other radio-loud AGN, with column densities ranging from a relatively modest $4 \times 10^{21} \text{ cm}^{-2}$ to a considerably large $6 \times 10^{23} \text{ cm}^{-2}$. A similar conclusion was drawn by Pihlström et al. (2003) based on HI radio absorption observations of a large sample of compact radio sources, and by (O’Dea et al. 2005) from upper limits to the molecular gas content in GPS sources. Note that the X-ray absorption gives more stringent constraints on the actual gas column densities than HI and molecular absorption densities, as X-ray absorption depends on the total column toward the central source, whereas radio observations only probe the neutral fraction of the gas. This is quite an important distinction since AGN are expected to create an extended ionised region, as we discuss in section 3.2. Furthermore, X-ray absorption probes the gas toward the accretion disk, whereas the radio absorption probes the neutral gas toward the radio source, which is situated at larger radii. It is therefore not surprising that for the four galaxies in our sample for which also HI absorption measurements have been made the HI column is always one to two orders of magnitude lower than the X-ray absorption column (Table 4 and Fig. 4). Attributing the difference solely to ionisation effects would mean ionisation fractions of 90% to 99%. However, the ionisation fractions are likely to be lower, because a substantial part of the X-ray absorption may occur inside the central 100 pc, which is not probed by absorption toward the radio hot spots.

Pihlström et al. (2003) found a strong anti-correlation between the linear size of the radio emission and the HI column density, which they use to probe the average density profile of the interstellar medium. They do not consider ionisation effects, whereas this could be an additional cause for the observed anti-correlation: small jets are associated with young AGN, which do therefore not yet have an extended narrow line emission region of ionised gas (see section 3.2). If this is the case it makes it less straightforward

to derive an average interstellar medium density profile from the relation between N_{HI} and linear size of the radio emission, since the growth of the emission line region also depends on the density and UV luminosity of the AGN.

3.2 The optical line emission: the case for an expanding emission line region

Usually a high [O III] luminosity is taken as an indication for the presence of a powerful AGN, but Fig. 2 indicates that GPS/CSO galaxies are relatively underluminous in [O III] compared to their radio or X-ray flux. This may not be too surprising if one takes into account that these are young radio galaxies, in which the AGN has switched on only a few thousand years ago. The reason is that it takes time to establish a large emission line region by photo-ionisation. This is best illustrated by a simple calculation, for which we assume an average interstellar medium density of 1 cm^{-3} and a typical luminosities of $\log L_{[\text{O III}]} = 42$, and $\log L_X = 44$. The number rate of ionising photons (i.e. $> 13.6 \text{ eV}$) is $\dot{N}_{\text{UV}} \sim 10^{54} \text{ ph s}^{-1}$ for a power law spectrum with photon index -1.75 . Comparing this to the total number of hydrogen atoms within a typical region of 5 kpc radius (Baum & Heckman 1989), one finds that $\sim 10^{67}$ atoms have to be ionised. In other words the central source has to shine for at least $\sim 10^{67}/10^{54} = 10^{13} \text{ s}$, or $\sim 300,000 \text{ yr}$ before it has completely ionized a region with a radius of 5 kpc. This means that if an AGN has become only recently active it must be surrounded by a small, but rapidly expanding ionisation nebula (see White et al. 2003, for a calculation concerning the first generation of quasars). Hence, this would imply that in GPS/CSO galaxies we see the birth of the narrow line region of radio-loud AGN.

In order to see whether this is the reason that GPS/CSO galaxies are relatively underluminous in [O III] we consider a simplified model for the evolution of a Strömgen sphere. For an old ionisation nebula in equilibrium, the number rate of ionising photons (\dot{N}_{UV}) should equal the number of recombinations, from which follows the equilibrium radius, R_i , of a Strömgen sphere:

$$R_i^3 = \frac{3\dot{N}_{\text{UV}}}{4\pi n_{\text{H}} n_{\text{e}} \alpha_{\text{H}}}, \quad (1)$$

with α_{H} the hydrogen recombination coefficient. The initial rapid expansion of the ionisation nebula is described by e.g. Spitzer (1968)

$$r_i^3 = R_i^3 \{1 - \exp(-n_{\text{e}} \alpha_{\text{H}} t)\}, \quad (2)$$

with r_i the radius of the ionisation front and t the time since the central source switched on. For small $n_{\text{e}} \alpha_{\text{H}} t$ we can approximate this by

$$r_i^3 \approx n_{\text{e}} \alpha_{\text{H}} t R_i^3 = \frac{3\dot{N}_{\text{UV}} t}{4\pi n_{\text{H}}} \quad (3)$$

The [O III] line emissivity is then given by

$$\dot{N}_{[\text{O III}]} = \frac{4\pi}{3} r_i^3 n_{\text{e}} n_{\text{OIV}} f_{5007\text{\AA}} \alpha_{\text{OIII}} = n_{\text{e}} \frac{n_{\text{OIV}}}{n_{\text{H}}} f_{5007\text{\AA}} \alpha_{\text{OIII}} \dot{N}_{\text{UV}} t, \quad (4)$$

with $f_{5007\text{\AA}}$ the probability of emitting a photon at 5007 \AA after recombination.

Assuming the interstellar medium densities in the GPS/CSO galaxies are more or less similar, we can expect the following correlation between the [O III] luminosity and the number rate of ionising photons for young GPS/CSO sources of kinematic age τ , pro-

vided that the age of the radio galaxy coincides with the birth of the ionisation nebula:

$$L_{[\text{O III}]} \propto \tau \dot{N}_{\text{UV}}. \quad (5)$$

As a first approximation we consider whether there is a relation between the observables $L_{[\text{O III}]}$, and τ and L_X . However, Fig. 5 illustrates that the five sources in our sample do not support a simple scaling of $L_{[\text{O III}]} \propto \tau L_X$. There may be various reasons why this is not the case: e.g. the interstellar medium density varies from galaxy to galaxy, there is no simple proportionality between L_X and \dot{N}_{UV} , due to different spectral energy distributions (different spectral slopes, or spectral breaks), and shocks induced by jet cloud interactions may provide an additional source of ionisation.³ Moreover, one of the outliers is B1358+624, for which we only have an approximate age.

However, a hint of what may the prime reason for deviations from Eq. 5 is provided by the very low [O III] luminosity of B0108+388, because this is also the source with the highest absorption column (Table 3). So the most likely reason that the optical emission is lower than expected is that the ionising UV flux is blocked by absorbing material close to the nucleus. The absorbing material is probably not the result of neutral hydrogen and helium, as, being close to the nucleus it would be ionised almost immediately, but dust grains, which may survive the extreme conditions close to the nucleus for 1000 yr to 10^6 yr , depending on the destruction mechanisms and dust particle sizes (e.g. Villar-Martín et al. 2001). For a young source like B0108+388 this means that an appreciable amount of dust may still enshroud the nucleus, frustrating the formation of a narrow emission line region. Note that this may also explain the relatively high neutral hydrogen column density of B0108+388 (Pihlström et al. 2003, Fig. 4); the hydrogen ionisation fraction of the inner stellar medium is likely to be low, which would also support the idea that photo-ionisation is the dominant source of ionisation. If ionisation is dominated by shocks generated by the jet, one would expect that B0108+388 would be relatively bright in [O III] as its interstellar medium density is apparently high. B1358+624 deviates less from the expected relation in the right hand panel of Fig. 5 due to its relatively flat X-ray spectrum, which makes that the number flux of UV photons is relatively small with respect to the X-ray luminosity. However, since we do not know the broad band spectral shape, we do not want to overemphasise this.

Let us now consider the possible implications of dust absorption. The optical depth of dust particles depends on dust particles cross sections ($\sigma_d = \pi r^2$ with r the physical size of the particles, $r \sim 0.1 \mu\text{m}$) and the column density of dust particles N_d . To obtain an order of magnitude estimate we assume that most dust particles consist of silicates, and that all silicon is depleted into dust. As $N_{\text{Si}} \approx 4 \times 10^{-4} N_{\text{H}}$, and a typical dust particle density is $\rho = 3.5 \text{ g cm}^{-3}$, we have $N_d \approx 10^{-13} N_{\text{H}}$, and the optical depth should be around $\sigma_d N_d = 3 \times 10^{-23} N_{\text{H}}$. This means that dust particles absorb an appreciable amount of UV flux if the hydrogen column density is comparable to, or exceeds, 10^{23} cm^{-2} , which is only the case for B0108+388. We have therefore extrapolated from the observed L_X the ionising photon luminosity \dot{N}_{UV} using the

³ Although we do not have kinematic age estimates of PKS1345+125 and Mkn668 (Guainazzi et al. 2004), reasonable values for the age in fact show these galaxies to be too bright in [O III] compared to the galaxies in our sample. In this case the reason is very likely that a large part of the [O III] emission is not related to the activity of the central nucleus, as both galaxies show evidence of recent merger activity, and are bright infrared sources.

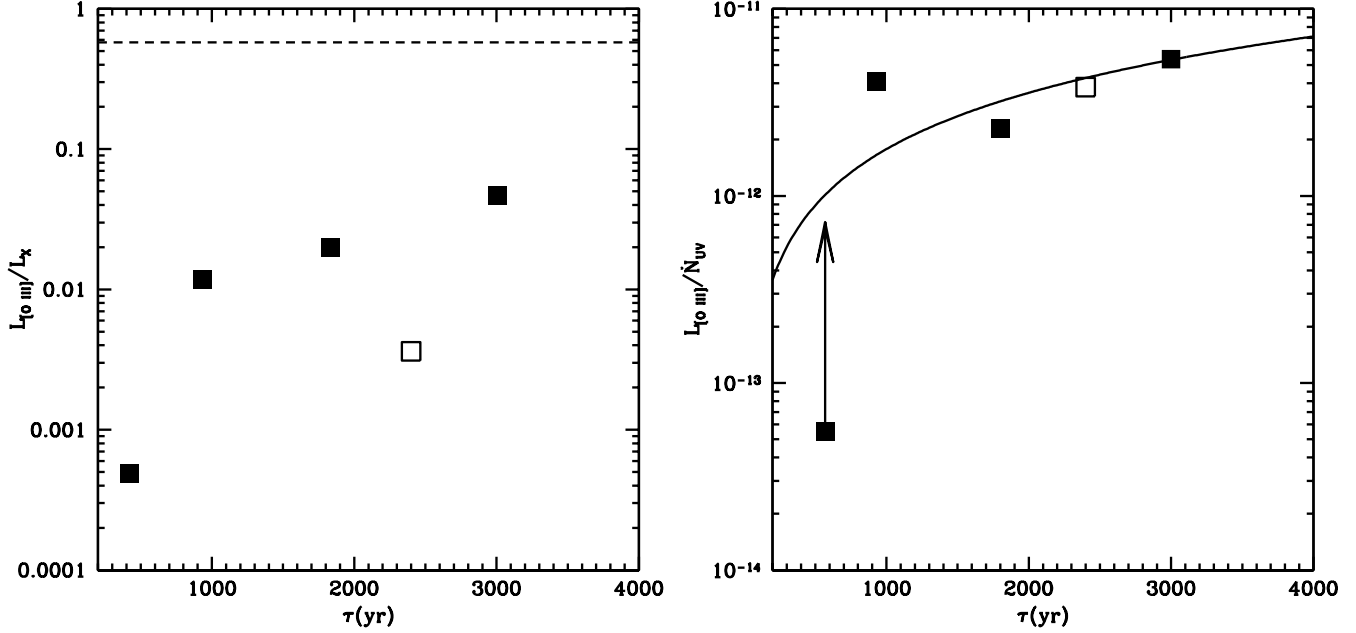


Figure 5. Left: The ratio of the $[\text{OIII}]_{5007\text{\AA}}$ and 2-10 keV X-ray luminosity versus the kinematic age of the radio source. The dashed line indicates the average value taken from Sambruna et al. (1999). Right: Similar to the left hand figure, but instead of L_X the extrapolated UV photon luminosity is used, derived from the X-ray luminosity using the power law slope in Table 3. The arrow indicates approximately how the ratios changes if the UV emission is obscured by dust assuming that the dust column density scales with N_H . This would only significantly affect B0108+388. The line shows the expected scaling for a young expanding narrow line region (eq. 5). B1358+624 is indicated with an open symbol, as its age is not based on a direct kinematic age measurement, but on its size (Table 1).

observed spectral properties. Plotting now $L_{[\text{OIII}]}$ as a function of $\tau \dot{N}_{\text{UV}}$ we see less scatter, certainly if we allow for dust absorption (Fig. 5). In order to bring B0108+388 on the expected relation we need a conversion of N_H to dust optical depth that is 16% of the above order magnitude estimate. Note that in a log-log plot the absorption enters linearly, since $\ln(\dot{N}_{\text{UV}-\text{abs}}) = \ln(\dot{N}_{\text{UV}}) - \sigma_d N_d$. Hence, only B0108+388 is likely to be significantly affected by dust absorption.

The large uncertainties in extrapolating from the observed L_X to an ionising UV flux makes that we cannot use Fig. 5 (right panel) to prove that Eq. 5 is an accurate description, but it makes it at least plausible that for GPS/CSO galaxies the $[\text{OIII}]$ emission is relatively low due to an underdeveloped narrow emission line region. This is consistent with the idea that GPS-galaxies have AGN that switched on around the same time that the radio jets were formed.

Further support for the idea that GPS/CSO galaxies are in the process of creating an extended narrow line region comes from the fact that neutral hydrogen apparently extends close to the compact radio jets, given the fact that there is strong anti-correlation between the neutral hydrogen column density and jet-size (Pihlström et al. 2003). Note that GPS/CSO galaxies have sizes of the order of a few 100 pc, whereas narrow emission line regions can extend up to 10 kpc.

3.3 The radio luminosity versus the X-ray luminosity

The X-ray emission from AGN is thought to come predominantly from the immediate vicinity of the central black hole, i.e. thermal emission from the accretion disk reprocessed by the hot plasma in its vicinity. It is unlikely that synchrotron radiation from the jet makes a dominant contribution to the X-ray band. The reason is

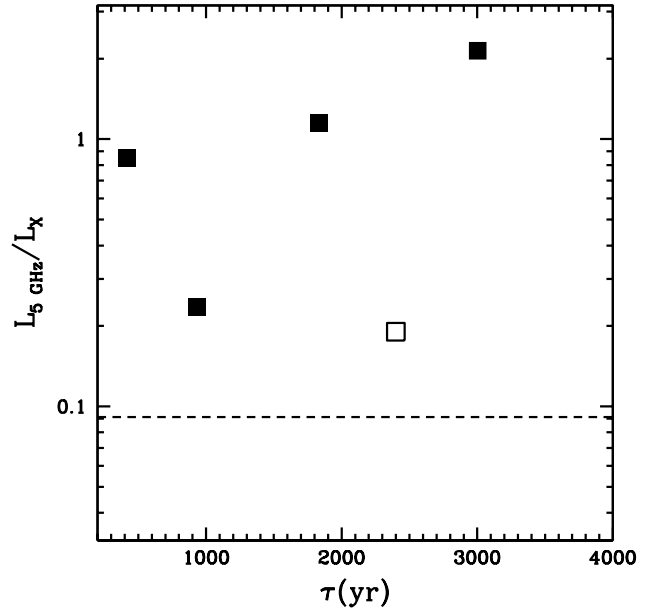


Figure 6. The ratio of the radio and X-ray luminosity versus the kinematic age of the radio source. The dashed line shows the average ratio for radio loud AGN galaxies with $\log L_X > 42$, taken from Sambruna et al. (1999). Only sources comparable in X-ray luminosity to our sample were chosen, because weaker X-ray sources appear to be relatively radio bright. Like in Fig. 5, B1358+624 is indicated with an open symbol.

that, given the typical magnetic fields inferred from radio luminosities (> 1 mG, O’Dea 1998), the synchrotron cooling time relevant for X-ray synchrotron radiation is in the order of only 2 yr for an electron energy of 10 erg. This means that a very small fraction of the total radio jet volume could produce X-ray synchrotron emission. Another potential source of X-ray emission from outside the central region could be inverse Compton emission by the relativistic electron population in the jets (c.f. Belsole et al. 2005). Although we cannot totally exclude a significant inverse Compton contribution, it seems unlikely to be the case for our sample. The reason is that the X-ray emission should in that case come from the same locations as the radio emission (the bright regions in the jets). However, we would then expect that the measured X-ray absorption columns would be more consistent with radio absorption measurements toward the jets, which is not the case (section 3.1).

It is therefore reasonable to assume that, compared to the radio and [O III] luminosity, the X-ray luminosity is more directly related to the accretion power of the AGN. Nevertheless, the radio and optical luminosities are still indirectly related to the accretion power, given the correlations between radio, optical and X-ray luminosities (e.g. Sambruna et al. 1999).

It is, therefore, interesting that GPS/CSO galaxies seem on average radio bright compared to the X-ray luminosity (Fig. 2). Given the absorption column distribution and low [O III] emission, we can ignore the interpretation that the radio emission is relatively bright because the interstellar medium is dense in GPS/CSO galaxies, as argued by advocates of the “frustrated radio source” scenario. It is, therefore, very probable that GPS/CSO galaxies are radio bright because they are young. However, within our sample no relation between age and radio over X-ray ratio can be seen (Fig. 6), nor is there a correlation with column density.

Nevertheless, the fact that for the sample as a whole the radio to X-ray luminosity is brighter than for other radio-loud AGN is at least qualitatively in agreement with several radio evolution models, such as Fanti et al. (1995); Readhead et al. (1996); Kaiser & Alexander (1997); Alexander (2000) and Snellen et al. (2000). These models describe the evolution of radio jets, with radio brightnesses depending on the radial density distribution of the interstellar medium. The radio jets are relatively bright as long as they plow through the dense regions of the galaxies, but decline as soon as they propagate outside the core of the galaxy. The difference between the various models is that some assume a density distribution described by a King profile (Snellen et al. 2000; Alexander 2000), whereas others assume a density profile falling off as power law of radius (Kaiser & Alexander 1997). As a result, the non-power law models predict that galaxies in the GPS-phase are still increasing in radio luminosity in time, until the jet has reached the core radius of ~ 1 kpc, after which the luminosity declines. In this case the relatively brightest phase of radio galaxies would be represented by the so-called compact steep spectrum sources (CSS), which have more extended radio jets than GPS/CSO sources. The power law density models predict that right after the jet emerges from the core region the radio emission starts to decline.

Our results are inconclusive regarding the details of the early evolution of the radio luminosity. However, future X-ray observations of CSS galaxies could help to clarify the brightness evolution further, as models with a King profile predict that CSS galaxies should, on average, have a higher radio to X-ray luminosity ratio than GPS/CSO galaxies, whereas models that assume power law density profiles predict that CSS galaxies should have a smaller radio to X-ray luminosity.

4 CONCLUSIONS

We have presented *XMM-Newton* observations of a sample of all the GPS/CSO galaxies with $|b| > 20^\circ$ from the Pearson & Readhead (1988) catalog, four of which have measured kinematic time scales for the jet expansion. All five of the sources are detected by *XMM-Newton* thereby increasing the number of X-ray detected GPS/CSO galaxies from 2 to 7. These detections allow us to compare the X-ray properties of GPS/CSO galaxies with those of other radio loud AGN.

The results presented here support the hypothesis that GPS/CSO galaxies represent the young phases in the evolution of radio-loud AGN. The alternative explanation that the radio sources are compact due to confinement by an exceptionally high density of the interstellar medium in those galaxies, seems extremely unlikely in view of the low intrinsic X-ray absorption column densities, which ranges from $N_H = 4 \times 10^{21} \text{ cm}^{-2}$ to $6 \times 10^{23} \text{ cm}^{-2}$, and has a distribution similar to other radio loud AGN. After submission of our manuscript, a preprint by Guainazzi et al. (2005) arrived at apparently different conclusions based on a sample of five different GPS galaxies observed by *Chandra* and *XMM-Newton*. Only one of the five GPS galaxies in their sample has $N_H < 10^{22} \text{ cm}^{-2}$, whereas this is $75\% \pm 26\%$ for their control sample. Note, however, that in our sample three out of five have $N_H < 10^{22} \text{ cm}^{-2}$. Taking both samples together, this means that four out of ten GPS galaxies, or $40\% \pm 20\%$ have $N_H < 10^{22} \text{ cm}^{-2}$ consistent with the control sample.

The fact that the absorption columns toward GPS galaxies are consistent with those of other radio galaxies suggests that the interstellar medium densities in the cores of GPS/CSO galaxies are similar to those of other radio loud AGN. A similar conclusion was reached by Pihlström et al. (2003) based on HI radio absorption observations, but the X-ray data provide stronger constraints, as the total column density contributes to the absorption, including ionized regions of the interstellar medium. This may contribute to the fact that in all cases the X-ray column densities are higher than the HI column densities. A difference between the radio column densities and the X-ray column densities is also that the X-ray column is measured toward the central source, whereas the HI column density is toward the jets, which extend outside the central region. If the difference between radio and X-ray column density is dominated by those geometrical effects, this would be additional evidence against the confinement scenario, since the jets have apparently been able to pierce through the dense local regions that contribute most to the X-ray absorption column.

Although the N_H distribution of our sample cannot be distinguished from other radio-loud AGN, the ratio of radio to X-ray luminosity shows that GPS galaxies have a strong tendency to be relatively radio bright. This supports the view that for the same thrust of the jets younger radio sources are relatively bright (Kaiser & Alexander 1997; Snellen et al. 2000). However, the data is inconclusive concerning whether GPS-galaxies represent the most radio-luminous phases in the lives of radio-loud AGN, as would be the case if the source develops in a density profile that drops off as power law with distance (Kaiser & Alexander 1997; Pihlström et al. 2003), or whether they are still in their brightening phase. This would be the case if the interstellar medium is best described by a King profile with a relative uniform density within ~ 1 kpc of the center and then dropping off as a power law (e.g. Snellen et al. 2000). In the latter case the brightest evolutionary phase of radio-loud AGN would be represented by the compact steep spectrum sources (CSS), which have more extended ra-

dio emission than GPS/CSO galaxies. A similar study to this one concerning CSS-galaxies can clarify this issue.

Finally, we find that GPS/CSO galaxies are relatively weak in [O III] line emission. This is again in support of the idea that GPS/CSO galaxies represent the very earliest stages of the evolution of radio-loud AGN, since narrow line regions need time to build up to their equilibrium size, and young narrow line regions are therefore not as bright as fully developed ones. The narrow line region is powered by the UV flux of the central source, but also shocks induced by the expanding jets are likely to contribute to their formation. For those very young radio-loud AGN we advocate here that their emission line regions are powered by the UV flux from the central sources. A case in point is that the relatively weakest [O III] source, B0108+388, has also the highest X-ray column density, which suggests that a dusty torus is partially blocking the UV light. The low [O III] luminosity therefore shows that the birth of the narrow emission line region must coincide more or less with the birth of the radio jet. However, we caution that we only have a limited knowledge of the nature of the ionization mechanism for the [O III] line emission. i.e. both shocks from the jets, as the UV radiation from the AGN may contribute to the ionization. Moreover, compact steep spectrum (CSS) sources, probably representing a more advanced evolutionary state of radio galaxies than GPS galaxies, show that the forbidden line emission tends to be aligned with the radio jet (de Vries et al. 1999). This phenomenon is not well understood, but it should be accounted for if one wants to build a more detailed model of the evolution of emission line nebulae in radio galaxies.

In summary, the findings from this X-ray study lends further support to the theory that GPS/CSO galaxies represent the early phases of radio-loud AGN, in which also the narrow line emission nebula is still in the early phases of its evolution. Future X-ray studies may help to further clarify the relation between age or jet-size, the extent or brightness of the emission line region and the power of the X-ray emission. It is important to include also compact steep spectrum (CSS) sources in such a study, as they are likely to represent the next phase in the evolution of radio-loud AGN. Comparing their X-ray to radio luminosity may help clarify whether the radio emission declines already during the GPS-phase, or first increases, then peaks around the CSS-phase and from then on weakens.

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